(NASA-CR-165455) DEVELOP AND TEST FUEL CELL POWERED ON-SITE INTEGRATED TOTAL ENERGY SYSTEMS. PHASE 3: FULL-SCALE POWER PLANT DEVELOPMENT Quarterly Report, May - Jul. 1981 (Engelhard Industries, Inc.) 35 p HC A03/MF A01 G3/44

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DEVELOP AND TEST FUEL CELL POWERED ON-SITE INTEGRATED TOTAL ENERGY SYSTEMS: PHASE III, FULL-SCALE POWER PLANT DEVELOPMENT 2ND QUARTERLY REPORT: MAY - JULY 1981

ENGELHARD INDUSTRIES DIVISION
ENGELHARD CORPORATION
EDISON, NJ 08818
A. Kaufman, Contract Manager
G. K. Johnson, Contract Technical Coordinator

REPORT DATE: August 25, 1981

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
UNDER CONTRACT DEN3-241

FOR
U.S. DEPARTMENT OF ENERGY
ENERGY TECHNOLOGY
DIVISION OF FOSSIL FUEL UTILIZATION
UNDER INTERAGENCY AGREEMENT DE-AI-01-80ET17088

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SECTION I. INTRODUCTION

Engelhard's objective under the present contract is to contribute substantially to the national fuel conservation program by developing a commercially viable and cost-effective phosphoric acid fuel cell powered on-site integrated energy system (OS/IES). The fuel cell offers energy efficiencies in the range of 35-40% of the higher heating value of available fuels in the form of electrical energy. By utilizing the thermal energy generated for heating, ventilating and air-conditioning (HVAC), a fuel cell OS/IES could provide total energy efficiencies in the neighborhood of 80%. Also, the Engelhard fuel cell OS/IES which is the objective of the present program offers the important incentive of replacing imported oil with domestically produced methanol, including coal-derived methanol.

Engelhard has successfully completed the first two phases of a five-phase program. The next three phases entail an integration of the fuel cell system into a total energy system for multi-family residential and commercial buildings. The mandate of Phase III is to develop a full scale 50kW breadboard power plant module and to identify a suitable type of application site. Toward this end, an initial objective in Phase III is to complete the integration and testing of the 5kW system whose components were developed during Phase II. Following the test of this sub-scale system, expected in August 1981, scale-up activities will be implemented as a total effort. Throughout this design and engineering program continuing technology support activity will be maintained to assure that performance, reliability, and cost objectives are attained.

SECTION II. TECHNICAL PROGRESS SUMMARY

TASK I - 5kW POWER SYSTEM DEVELOPMENT (97046)

This task is of limited duration (approximately two more months) and has as its objective the complete integration of 5kW components developed during Phase II. This integrated 5kW system will be automated under microprocessor control.

REFORMER

Modifications to the 5kW reformer have been completed. These modifications were designed to reduce the reheating effect on the exit gas and were detailed in the April Quarterly Report. Check-out runs have been made, and the tendency of process gas to be reheated has been reduced, but not eliminated entirely. The performance of the unit was satisfactory, including operation at an overload condition of 140% of design capacity. The reformer has been installed in the 5kW power system.

During one recent run at 100% of design load, data were taken to allow calculation of the thermal efficiency of the 5kW reformer/burner as presently designed and insulated. For the particular run considered the air flow rate to the burner was 2.4 times stoichiometric, but other parameters of operation had their normal values (see later in Table I). A complete enthalpy balance was calculated for the unit based upon the known compositions, flow rates and temperatures of all inlet and exit streams. The streams included were:

Simulated anode vent gas in at 298 K.
Combustion air in at 298 K.
MeOH/H_2O feed vapor in at 377 K.
Flue gas out at 577 K.
Product gas out at 566 K.

SECTION II. - CONTINUED

The change in enthalpy was calculated separately for the process streams (Q_p) and for the combustion streams (Q_c). Defining a heat-transfer effectiveness factor as Q_p/Q_c, the result for the run considered is 0.58. The corresponding thermal efficiency, defined as the heating value of the net hydrogen output from the fuel processor (hydrogen generated less hydrogen consumed in the burner) divided by the heating value of the methanol fed to the fuel processor, is 0.86.

FUEL CELL STACK

The 5kW stack has been assembled with 80 cells. The components used for construction were essentially those described in the April Quarterly Report with the exception of the ABA bipolar plates. These were originally intended to be of the new, unitized type of construction based upon needled-felt A-elements. With this method of fabrication, however, a problem of plate warpage developed, and plates of an alternate design were made for this stack by Pfizer. The plates produced by Pfizer consist of two needled-felt A-elements and discrete, gas-impermeable B-elements, all bonded together with graphite adhesive. The plates are entirely carbon and remain flat when grooves are cut for reactant distribution.

The stack will be qualified by brief testing during August, after which it will be integrated into the complete 5kW power system.

INTEGRATED SYSTEM

Physical integration of the 5kW power system has been started. Acquisition of ancillaries is complete. The only item being awaited is the stack, which has been assembled and is undergoing qualification

testing. The system is being mounted on two moveable carts for portability. The inverter is a separate floor unit which will stand alongside the carts.

A complete system schematic is shown in Figure 1. Not indicated is an acid-mist trap to be installed between the cathode exit and the air heat exchanger. The specification of flow streams at various points in the system at design load conditions is given in Table I, and the coding of components in Table II.

Documentation of software for microprocessor control of the 5kW power system has been completed. The central unit in the control sub-system is a Zilog Z-80 microprocessor. Operation of the software and microprocessor has been checked-out by the use of an analog voltage simulator which provides variable input voltages analogous to transducer outputs in the actual integrated power system.

An operations manual for the 5kW power system has been completed.

Physical integration of the power system will be completed in late August. A test of 500 hours will begin as soon as integration is completed. Thus Task I of the contract is expected to be completed in September.

TASK II - ON-SITE SYSTEM APPLICATION ANALYSIS (97047)

The purpose of this task is to develop an application model for on-site integrated energy systems, with some emphasis on a system of 50kW (electrical) modular capability. The model will consider fuel availability and costs, building types and sizes, power

SECTION II. - CONTINUED

distribution requirements (electrical and thermal), waste heat utilization potential, types of ownership of the OS/IES, and grid connection vs. stand-alone operation. The work of this task is being carried out under sub-contract by Arthur D. Little, Inc.

Accumulation of a building and energy data base has been started. A meeting was held on July 29 between A.D.L. and Engelhard to confirm the general approach and exchange technical information. Milestones for the sub-contract were agreed upon and scheduled. These will be, for the most part, specific recommendations of preferred sites arrived at by use of the model. The approach used by A.D.L. will be, first, to complete all aspects of a study model of a power system for a garden apartment complex; following this, data on other types of buildings will be fed into the same model.

TASK III - ON-SITE SYSTEM DEVELOPMENT

This task forms the core of the Phase III Contract. Work under this task will result in the breadboard design of a system for an on-site application. The power plant will be designed for a rated output of 50kW (electrical) or some multiple thereof. The fuel processor and power conditioner will each be 50kW modules, while the 50kW fuel cell will comprise two 25kW stack modules. This task is accordingly broken down into four sub-tasks as follows:

- 3.1 Large Stack Development (97048)
- 3.2 Large Fuel Processor Development (97038)
- 3.3 Overall System Analysis (97051)
- 3.4 Overall System Design and Development (97064)

A large part of Sub-task 3.3 is being carried out by Physical Sciences, Inc. (PSI) under subcontract.

LARGE FUEL PROCESSOR DEVELOPMENT (97038)

The one-dimensional mathematical model (axial temperature profile) for the methanol/steam reformer has been upgraded. The model predicts temperature profiles for process and flue gases, compositions of reactants through the catalyst bed (including CO via the shift reaction), and heat transfer coefficients. The numerical solutions of differential equations were obtained by either the Euler (first-order) method or the Runge-Kutta (fourth-order) method on the PDP 11/34 computer at Engelhard.

Two notable features of the model prediction are the parallelism between methanol conversion and equilibrium CO (Figure 2) and the large increase in process gas heat transfer coefficient as it becomes enriched in H_2 (Figure 3).

The model has used second-order kinetics since this was tentatively established from experimental data. The model, however, is rather insensitive to reaction order. The program is being generalized to include both first- and second-order kinetics as alternatives.

An additional program listing has been acquired which will allow expansion of this model to two dimensions (radial as well as axial).

A single-tube reformer has been designed and fabricated. In this initial unit a 50 mm (2 in) reactor tube is used. A sketch of this unit is shown in Figure 4. Temperature profiles will be obtained both radially and axially to interact with the two-dimensional mathematical model. Ancillary equipment is presently being installed to complete a test station for this and future single-tube reformers.

OVERALL SYSTEM ANALYSIS (97051)

Overall system analysis will consist of both steady-state and off-design analysis. Most of the modules required for a steady-state model of the proposed one atmosphere power plant have been completed. The steady-state main program was divided into three sections: a steady-state power plant section, a turbo-charged steady-state power plant section and a steady-state heat recovery section that would include the power plant water recovery condensers and the heating and ventilation systems, EIHVAC. A main program was written and run for the one atmosphere plant that was complete, except for the calculation of parasite losses.

In the process of running this system a number of improvements to other modules in the library were made to get the system to converge on results faster. These changes included minor modifications to the HX modules that allow the analyst to specify a broader range of parameters when sizing a heat exchanger. In the past, some of these parameters could only be specified implicitly with a SECANT loop; the new module computes the heat exchanged and the output temperatures explicitly and in much less time. Work was also started on the turbo-charged power plant and the EIHVAC section. This work included the development of a new version of THERMO which computes the enthalpy and heat of dilution for mixtures of phosphoric acid and water.

A module called LIQVP has been written to calculate the vapor pressure of water and methanol in various mixtures. Excellent agreement was obtained between the data and a curve fitted by means of two sets of four-suffix Margules coefficients, one for water and one for methanol. Engelhard has already found this useful as a means of calibrating the gas chromatograph used to analyze gases containing water and methanol vapor.

SECTION II. - CONTINUED

The fuel cell stack performance equations have been modified to reflect current Engelhard developments. The module called PERF was modified to allow for changes in cell resistance and catalyst loading.

PSI has received Engelhard's initial specifications for a 50kW power system, the inverter performance data, and a proposed HVAC sub-system.

The short-term goals at PSI are to incorporate the parasitic losses in the program for the one atmosphere plant, reconfigure and write a main program for the turbo-charged plant and then write the heat recovery program to complete the steady-state work. The only innovation required in these sections appears to be the constant temperature de-humidifier in the EIHVAC portion of the heat recovery section.

OVERALL SYSTEM DESIGN AND DEVELOPMENT (97064)

Detailed design work is in progress on components for an air-conditioning system run by waste heat from a 50kW fuel cell.

Tentative information and specifications for a 50kW DC-to-AC inverter have been supplied by Abacus Controls, Inc. of Somerville, N.J.:

Required input voltage	175 - 240 VDC
Output voltage	120/208 60 HZ 3ø
Efficiency @ 75 - 100% load	90+%
@ 25% load	80%

SECTION II. - CONTINUED

Voltage regulation	1%
Frequency regulation	0.25%
Harmonic distortion	3%
Soft start no overshoot	40 VAC to 208 VAC
Volume	est. 120 cu. ft.
Weight	est. 2600#
Unit cost (includes power grid sync.)	est. $45,000
Projected cost @ 2000 units/yr.	est. $250/kW 1981 dollars

The efficiency versus load curve is almost flat between 75% and 100% inverter loading and falls to 80% efficiency at 25% inverter loading.

This efficiency fall-off is caused by losses in the inverter input filter, inverter bridge, output transformer, AC filter, DC circuitry power supply and inverter cooling fans, all of which add up to approx. 5.5 kW power loss at full load; this total decreases to about 2.5 kW at no load.

TASK IV - STACK SUPPORT (97049)

The purpose of this task, which will continue throughout the contract, is to investigate new materials and component concepts by experimentation and the use of small-stack trials. The criteria for choosing activities under this task will be the possibilities of improved performance or reduced cost, or both. Improvements in, and performances of electrocatalysts, though generated under Engelhard-sponsored Task VI, will be reported under Task IV.

SECTION II. - CONTINUED

ABA BIPOLAR PLATES

A problem of warpage has been encountered in the fabrication of ABA plates of unitized construction. Some progress has been made toward understanding the reason for the warpage and there are indications that varying the fabrication conditions may alleviate this problem. Work will continue in this area, but plates needed for stacks in the immediate future will be fabricated by the alternative method of fabrication implemented at Pfizer (see Task I, above).

Recently a new treatment has been developed that considerably improves the cost and effectiveness of the process used for edge-sealing the needled-felt A-elements.

3-CELL STACK TESTING

A 3-cell stack with a new, semi-automatic acid replenishment system has completed 3000 hours of testing at 464K (191°C). The performance of this stack is shown in Figure 5 (voltage at standard current density - 161 mA/cm^2) and in Figure 6 (open-circuit voltage). The electrolyte management system has operated successfully, supplying acid by cell-demand to make up for losses during cell operation. A small decrease in the average cell voltage during the last 1000 hours from 610 mV to 600 mV is attributed to partial flooding of the electrode support.

A new 3-cell stack utilizing improved electrocatalysts as well as a semi-automated acid replenishment system has been assembled and tested for 500 hours at 464K (191°C). A stable and high performance is indicated in Figure 7 (voltage at standard current density) and Figure 8 (open-circuit voltage). The average cell voltage at

standard current density is about 640 mV. This high value is attributed in large part to the two cathodes that are of an advanced, stabilized-Pt type. The cell voltage in these two cells is higher than the average of 640 mV, while the voltage of the top cell, with a standard Pt-on-carbon cathode catalyst, is somewhat lower than the average.

A synthetic reformate gas containing 2% CO and 65% H_2 was fed to this stack under conditions of approximately 70% H_2 utilization. The current/voltage curve for one cell on this fuel is shown in Figure 9, and for the entire stack in Figure 10. In each case the performance curve on pure H_2 is given for comparison. The single-cell voltage penalty in shifting from H_2 to reformate at 161 mA/cm^2 (150 A/ft^2) is unusually high at about 35 mV. This result is being studied further.

COOLING PLATES

As described previously, a method has been developed for the protection of aluminum cooling plates against corrosion. Subsequent experience has shown that the risk of corrosion has been greatly reduced but not yet entirely eliminated. A completely new design for cooling plates using no metals is under development. Details of this design will be described in a subsequent report.

TASK V - FUEL PROCESSING SUPPORT (97050)

The intent of this task is to provide background data and information to support the design and construction of an optimized 50 kW fuel processor under Task III. This support function will continue throughout most of the period of the contract. It is

envisioned that most of the effort of this task will be devoted to screening and longevity testing of catalysts for methanol/steam reforming.

After two false starts, due to equipment failure and contamination, a qualifying test run was completed on 1/8" T2107RS methanol reforming catalyst. The duration of the initial portion of the test (on commercial MeOH) was 625 hours at a temperature of about 527K (254°C) and a weight-hourly-space-velocity (WHSV) of 0.88 kg feed/kg catalyst-hour. This space velocity was deliberately set at about twice the usual value employed in, for example, a 5kW reformer in order to place a more severe test on the catalyst. Likewise, the temperature was set about 20 K below nominal design value in order to obtain incomplete methanol conversion from the beginning of the test. The results of this portion of the run are given in Table III. The initial levels of conversion, to 360 hours, are 5 to 10% higher than had been seen previously with 3/16" pellets of the same catalyst. At 360 hours a new batch of MeOH/H_2O feedstock was introduced. This feed was later found to be cloudy, indicating some impurity present. The impurity could not be identified by gas chromatography. It is thought that this is the reason for the apparent decline in activity beyond 360 hours. The catalyst itself is considered acceptable on the basis of this qualifying run.

In a continuation of the sub-scale qualification test, the catalyst was deliberately poisoned with 800 ppm of ethanol in the feed. Ethanol poisoning was continued for 180 hours, during which the methanol conversion dropped from 73% to 50%. The period of poisoning was between hours 625 and 816. (See Table IV.) When clean methanol/water feed was resumed, conversion recovered to only 55% (average). Originally this poisoning test was to continue for 1000 hours; however, it was cut short in view of the severity of the effect of ethanol. The used catalyst will be tested for possible coke formation.

SECTION II. - CONTINUED

TASK VI - IMPROVED ELECTROCATALYSTS (97039)

Developmental electrocatalyst formulations are being prepared under Engelhard sponsorship. These are provided to the main program, and results are reported under Task IV.

SECTION III. CURRENT PROBLEMS

None.

SECTION IV. WORK PLANNED

TASK I

- Qualifying tests for 5kW stack to be run.
- Integration of 5kW power system to be completed.
- 500 hour test of 5kW system to be started.

TASK II

- A. D. Little, Inc. to continue acquisition of data base and development of energy model of garden apartment complex.

TASK III

- Test station for single-tube reformer studies to be completed.
- Scale-up of ABA plates to be initiated by Pfizer.

TASK IV

- Test of semi-automatic acid replenishment system on 3-cell stacks to continue.

TASK V

- Qualification testing of UCI catalyst C70-2RS for methanol reforming to begin.

SECTION V - FINANCIAL MANAGEMENT ANALYSIS

TASK I - 5kW POWER SYSTEM DEVELOPMENT

Manpower expenditures for this task accelerated substantially in July reflecting intensive effort to bring the 5kW stack into readiness. Materials expenditures (already in excess of budget for this task because of incremental bipolar plate costs borne in bringing the needled-felt material into readiness for the 5kW stack in place of the reticulated vitreous carbon) were minimal in July. The total budget for this task has been exceeded, however, because of the incremental materials costs.

Stack testing is scheduled to take place in August.

TASK II - ON-SITE SYSTEM APPLICATION ANALYSIS

The Task II effort is being performed under a subcontract to Arthur D. Little, Inc. The Engelhard role will consist almost entirely of guidance and supervision. Work under the subcontract was initiated in June. Invoices have not yet been issued.

The 12-month subcontract will provide important perspective relating to system configuration and optimization under Task III. Information relating to selection of an application type will be derived from the subcontract as early as possible.

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SECTION V - CONTINUED

TASK III - ON-SITE SYSTEM DEVELOPMENT

1. Large Stack Development

Effort on this sub-task has produced a preliminary 25 kW stack design. Manpower expenditures were scheduled to increase substantially in July, but these remained similar to those of prior months because of intensive effort on Task I.

2. Large Fuel Processor Development

Work on this sub-task intensified during July - as called for in the program schedule. The setting up of single-tube reactor facilities is proceeding. Materials expenditures are in line with the pro-rated budget.

3. System Analysis

Minor in-house expenditures have been accumulated on this sub-task thus far (in accord with the plan). The main effort is being pursued through the PSI subcontract, in which the progress and expenditures are proceeding according to plan. (No invoice was received during this reporting period.)

4. System Integration

Effort on this sub-task through July is well above the budgeted rate for this period. A major increase in effort was scheduled for July, but prior effort allowed this to be scaled back. Activity has been concentrated in the HVAC sub-system area to lay the groundwork for the A. D. Little sub-contract effort, as well as on microprocessor development work for the control system.

SECTION V - CONTINUED

TASK IV - STACK SUPPORT

Activity during July in the stack support area continued to focus on acid-management schemes and evaluation of developmental cathode catalysts. Various three-cell stacks devoted to acid-management studies continued to operate.

Manpower expenditures through July remained about 25% below the planned level, primarily due to concentrated effort on Task I and control system development. The Pfizer subcontract for bipolar plate scale-up and cost reduction development has not yet been issued. Materials expenditures are somewhat low thus far.

TASK V - FUEL PROCESSING SUPPORT

Sub-scale fuel processing support testing is continuing, primarily involving qualification of large batches of catalyst. Manpower expenditures are below planned levels due to emphasis on Task III, Sub-Task 2.

TASK VI - IMPROVED ELECTROCATALYSTS

The development of advanced anode and cathode catalysts is proceeding under Engelhard sponsorship. Evaluation of these catalysts is accomplished under Task IV.

TASK VI - MANAGEMENT AND DOCUMENTATION

Expenditures in the management and documentation area are proceeding substantially according to plan.

Table I

Flow Rates in the 5kW Integrated System at Design Output Conditions

(Keyed to Figure 1.)

Location	Feed	Rates
B1	Combustion Air	With MeOH: 9.3 SCMH* (330 SCFH*) With anode vent gas: 3.4 SCMH (120 SCFH)
B2	Combustion Air	31 SCMH (1100 SCFH)
B3	Cathode Air	34 SCMH @ 2.6 kPa, 41 kg/hr (1200 SCFH @ 10" H_2O, 90 lb/hr)
BR1	(Start-up)	Same as P1.
	H_2	1.4 SCMH, 0.14 kg/hr (50 SCFH, 0.3 lb/hr)
	CO_2	2.5 SCMH, 4.63 kg/hr (87 SCFH, 10.2 lb/hr)
	(Anode vent gas)	
P1	Liquid MeOH	0.0019 m^3/hr @ 790 kPa, 32,000 kJ/hr (0.5 gal/hr @ 100 psig, 30,000 Btu/hr)
P2	Liquid MeOH	0.0064 m^3/hr @ 790 kPa, 105,000 kJ/hr (1.7 gal/hr @ 100 psig, 100,000 Btu/hr)
P3	Liquid MeOH/H_2O (1/1.3)	0.00579 m^3/hr @ 200 kPa, 5.27 kg/hr (1.53 gal/hr @ 15 psig, 11.6 lb/hr)
P4	Therminol Coolant	1.6 m^3/hr @ 200 kPa (7.0 gal/min @ 15 psig)
Anode Inlet (Reformate)	H_2	7.08 SCMH, 0.64 kg/hr (250 SCFH, 1.4 lb/hr)
	CO_2	2.46 SCMH, 4.63 kg/hr (87 SCFH, 10.2 lb/hr)

* Standard Cubic Meters per Hour, Standard Cubic Feet per Hour.

Table II

Component Codes

(Keyed to Figure 1.)

B	Blower
BR	Burner
CV	Check Valve
FS	Flow Switch
P	Pump
RV	Relief Valve
S	Solenoid Valve
TS	Thermocouple

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Table III

Sub-Scale Methanol/Steam Reforming Catalyst Test

Water/Methanol Molar Feed Ratio : 1.3

Catalyst: UCI T2107RS Copper-Zinc
1/8" x 1/8" pellets (10 cc in 90 cc alpha alumina, mixed logarithmically)

Hrs. on Stream	Avg. Bed Temp. K	Exit Bed Temp. K	% CO	WHSV**	% MeOH Conversion	Kinetic Rate Constant, k *
24	526.7	533.0	0.49	0.88	94.37	-
120	526.3	528.0	0.44	0.88	87.1	.165
194	527.2	525.2	0.41	0.88	85.65	.153
288	527.5	527.3	0.37	0.88	86.84	.163
360	527.6	527.7	0.33	0.88	87.09	.165
458	525.4	535.3	0.49	0.79	78.5	.0865
506	526.1	567.0	0.49	0.86	73.65	.0998
600	528.4	527.2	0.50	0.86	73.42	.1003
625	529.2	529.4	0.51	0.85	73.2	.0849

$$* \quad k = \left[\frac{\text{kg MeOH Feed}}{\text{kg reduced catalyst x hr}}\right] \cdot \left[\frac{\text{m}^3 \text{ Feed}}{\text{kg-moles feed}}\right]$$

** Weight-hourly-space-velocity, kg feed/kg catalyst-hr

NOTE: This table was inadvertently omitted from the May Monthly Report.

Table IV

Sub-Scale Methanol/Steam Reforming Catalyst Test

Water/Methanol Molar Feed Ratio = 1.3

Catalyst: UCI T2107RS Copper-Zinc
1/8" x 1/8" pellets (10 cc in 90 cc alpha alumina, mixed logarithmically)

Hrs. On Stream	Avg. Bed. Temp. k	Exit Bed Temp. k	% CO	WHSV**	% MeOH Conversion	Kinetic Rate Constant, k *
625	529.2	529.4	0.51	0.86	73.2	.0818
673	510.1	509.1	0.67	0.88	51.8	.0379
768	510.1	513.1	0.69	0.88	50.6	.0363
792	511.4	511.1	0.69	0.88	50.9	.0367
816	512.2	510.4	0.63	0.88	49.9	.0354
863	511.9	509.5	0.54	0.87	60.77	.0517
936	509.8	510.4	0.43	0.86	57.2	.0450
959	509.1	512.4	0.46	0.86	54.9	.0414
1030	510.3	510.6	0.49	0.87	54.7	.0416
1153	511.5	511.1	0.66	0.43	64.5	.0293
1177	511.2	511.1	0.60	0.43	64.9	.0297

$$* \quad k = \left[\frac{\text{kg MeOH Feed}}{\text{kg reduced catalyst x hr}}\right] \cdot \left[\frac{\text{m}^3 \text{ Feed}}{\text{kg moles feed}}\right]$$

** Weight-hourly-space-velocity, kg feed/kg catalyst-hr

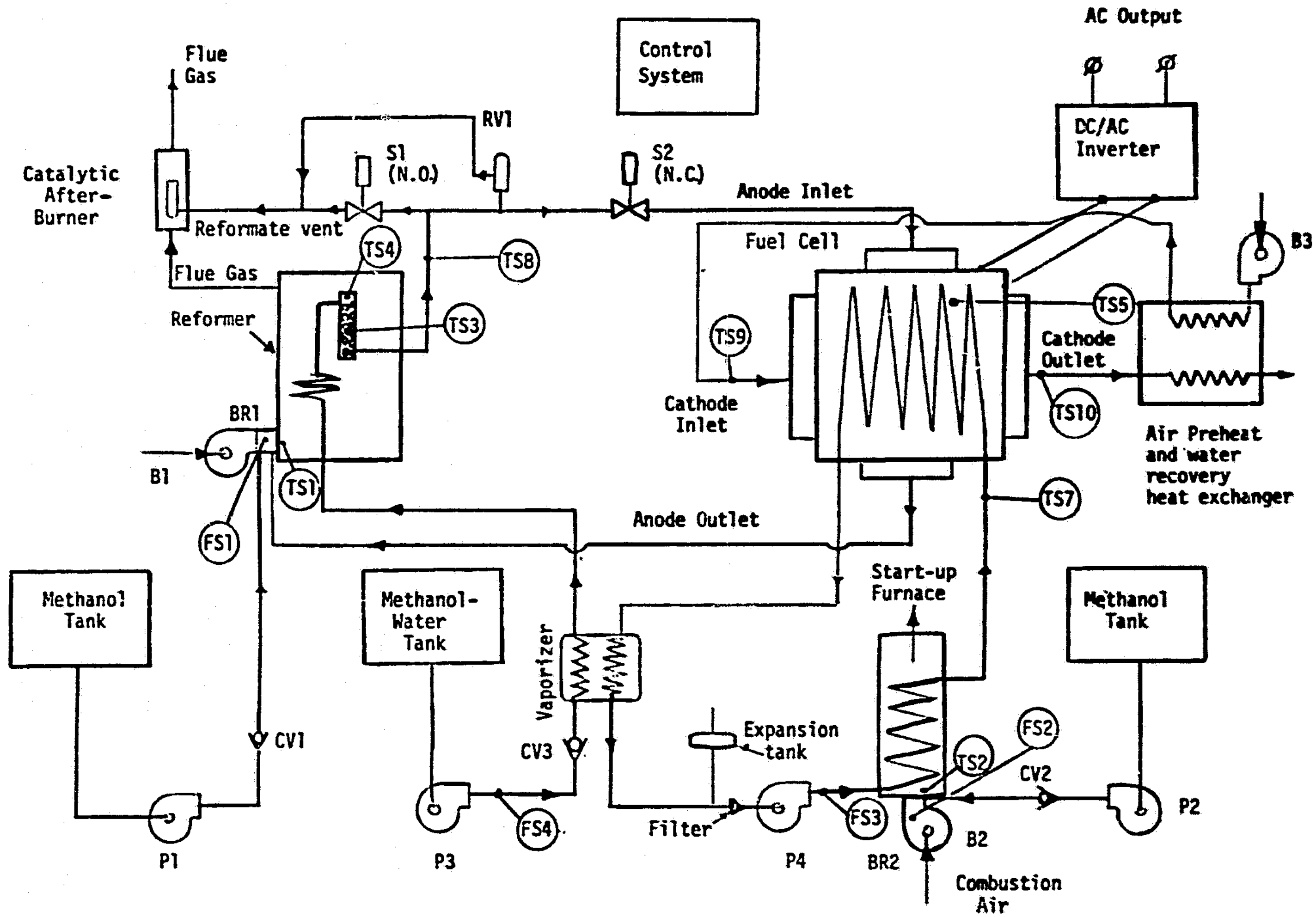

FIGURE 1 SCHEMATIC OF THE 5KW INTEGRATED SYSTEM

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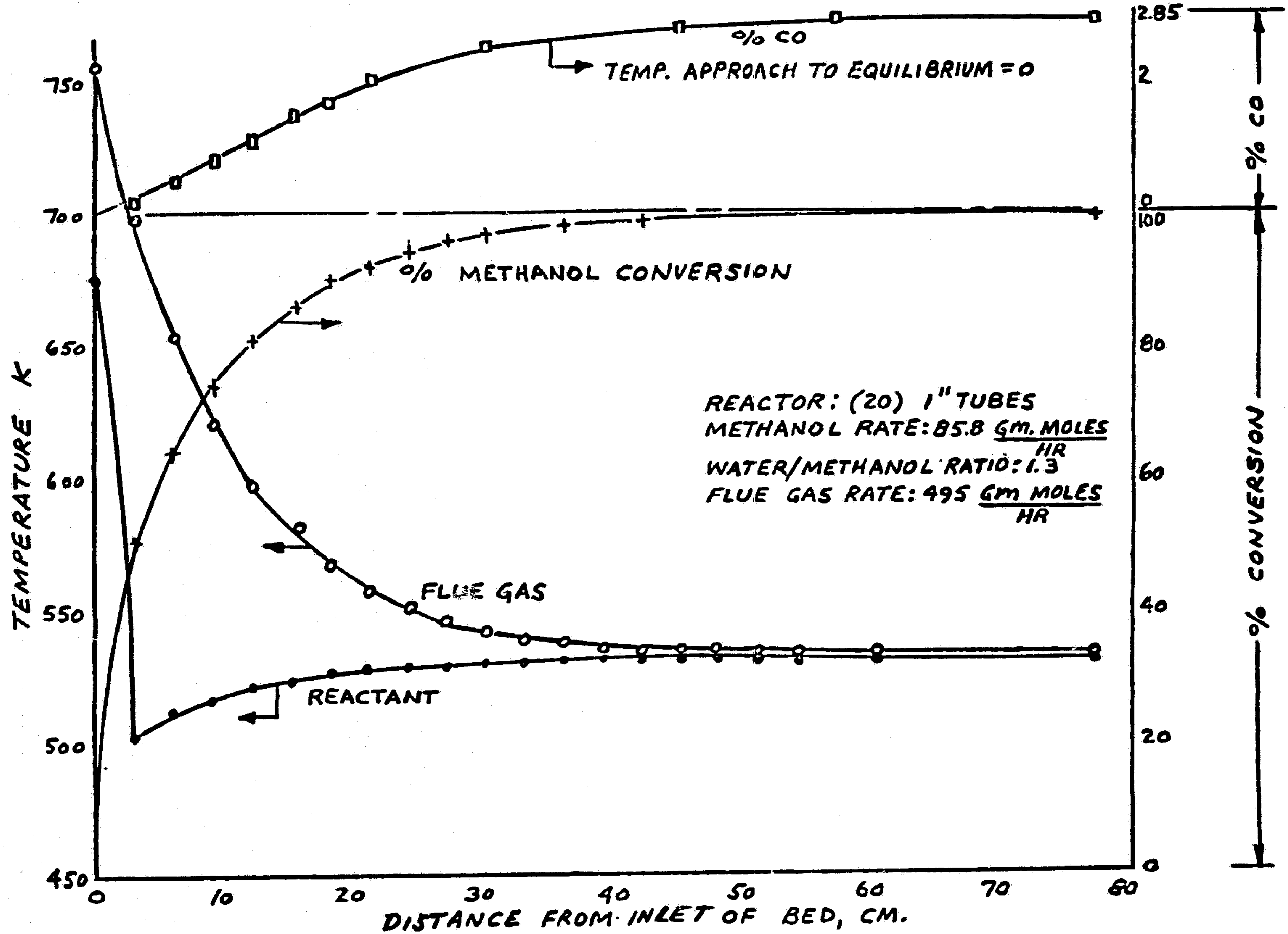


Figure 2 Predictions for 5kW Reformer from One-Dimensional Mathematical Model

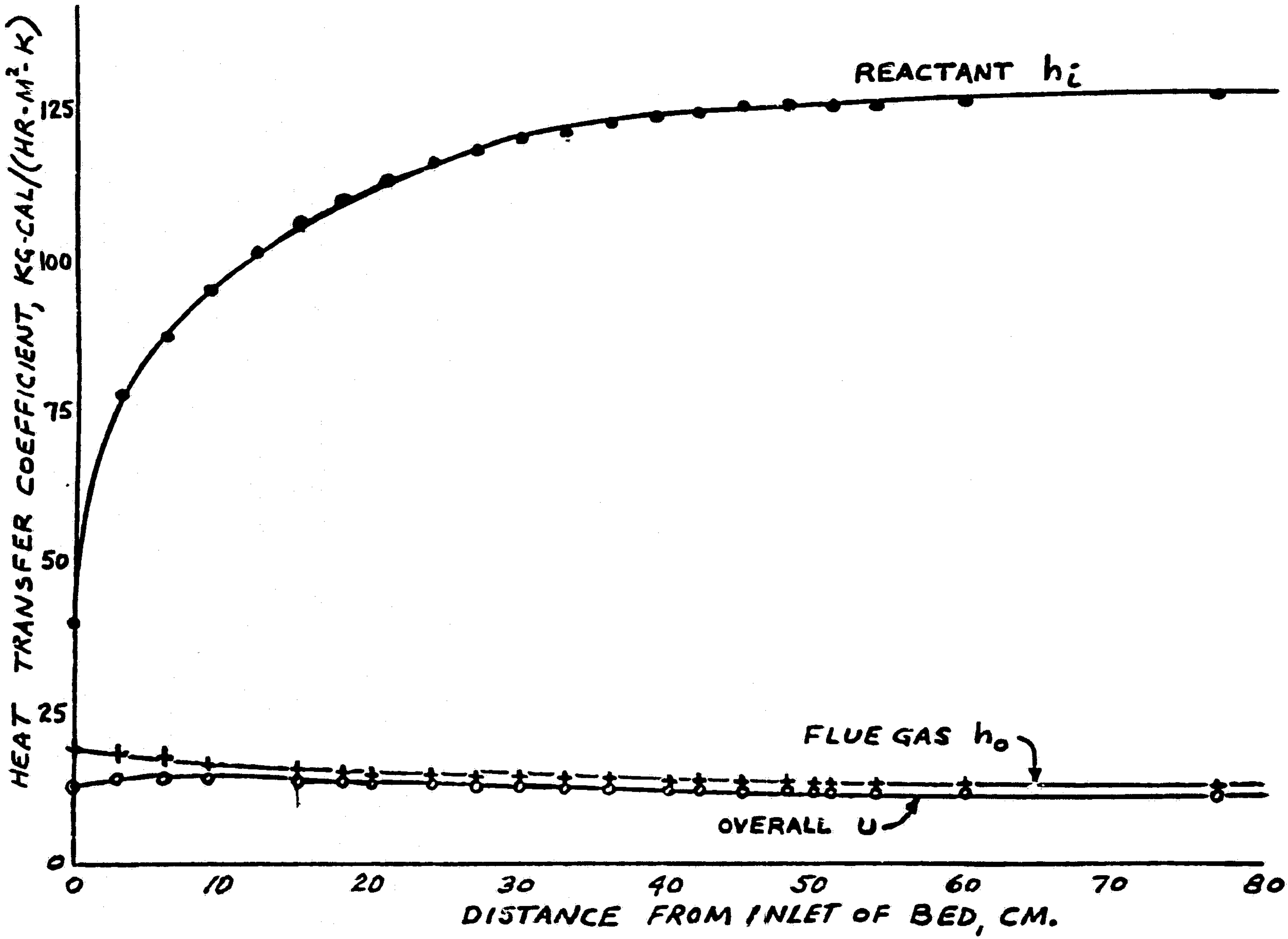


Figure 3 Heat Transfer Coefficients Predicted for 5kW Reformer from One-Dimensional Mathematical Model

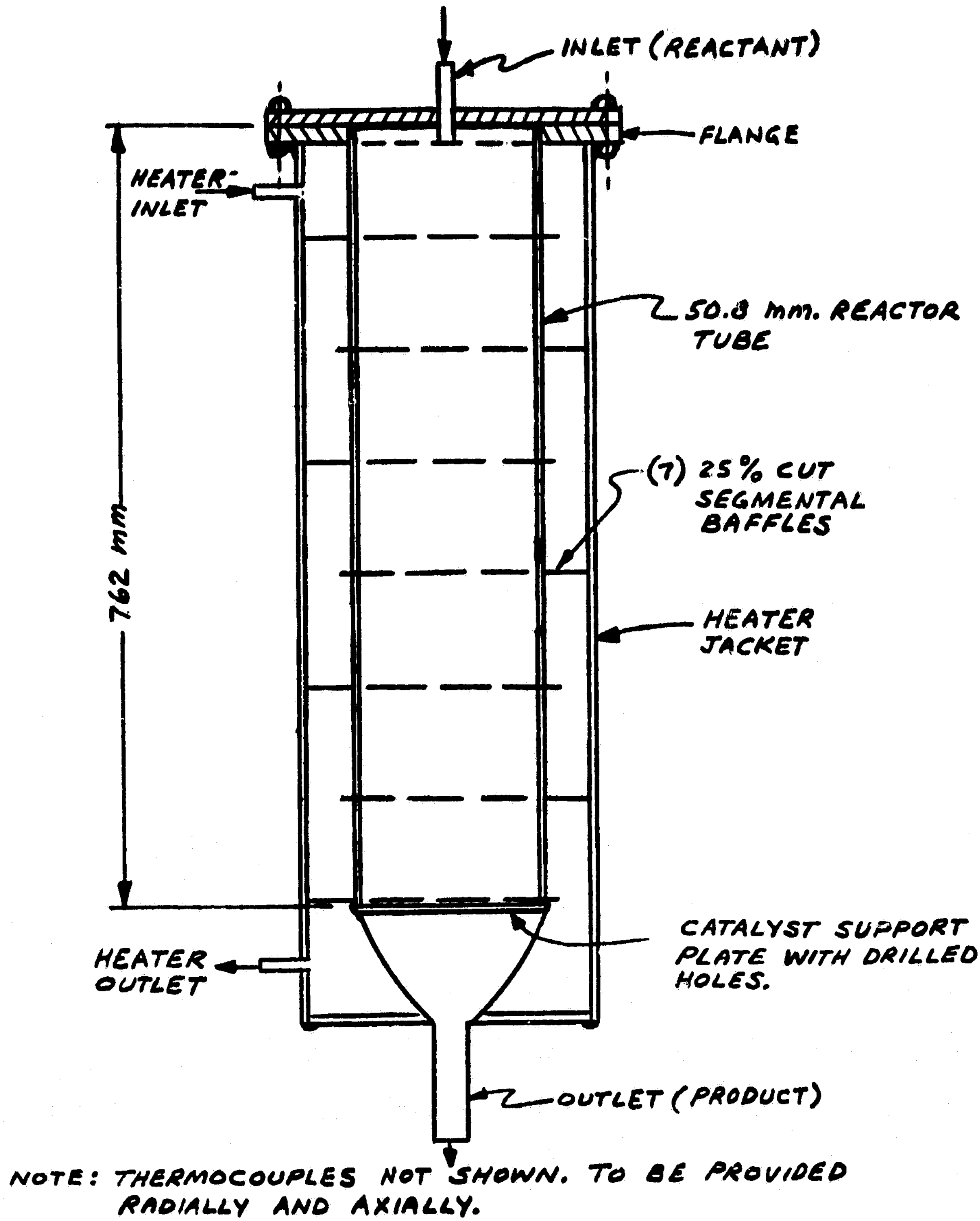


FIGURE 4 PRELIMINARY SKETCH OF EXPERIMENTAL SINGLE-TUBE REACTOR

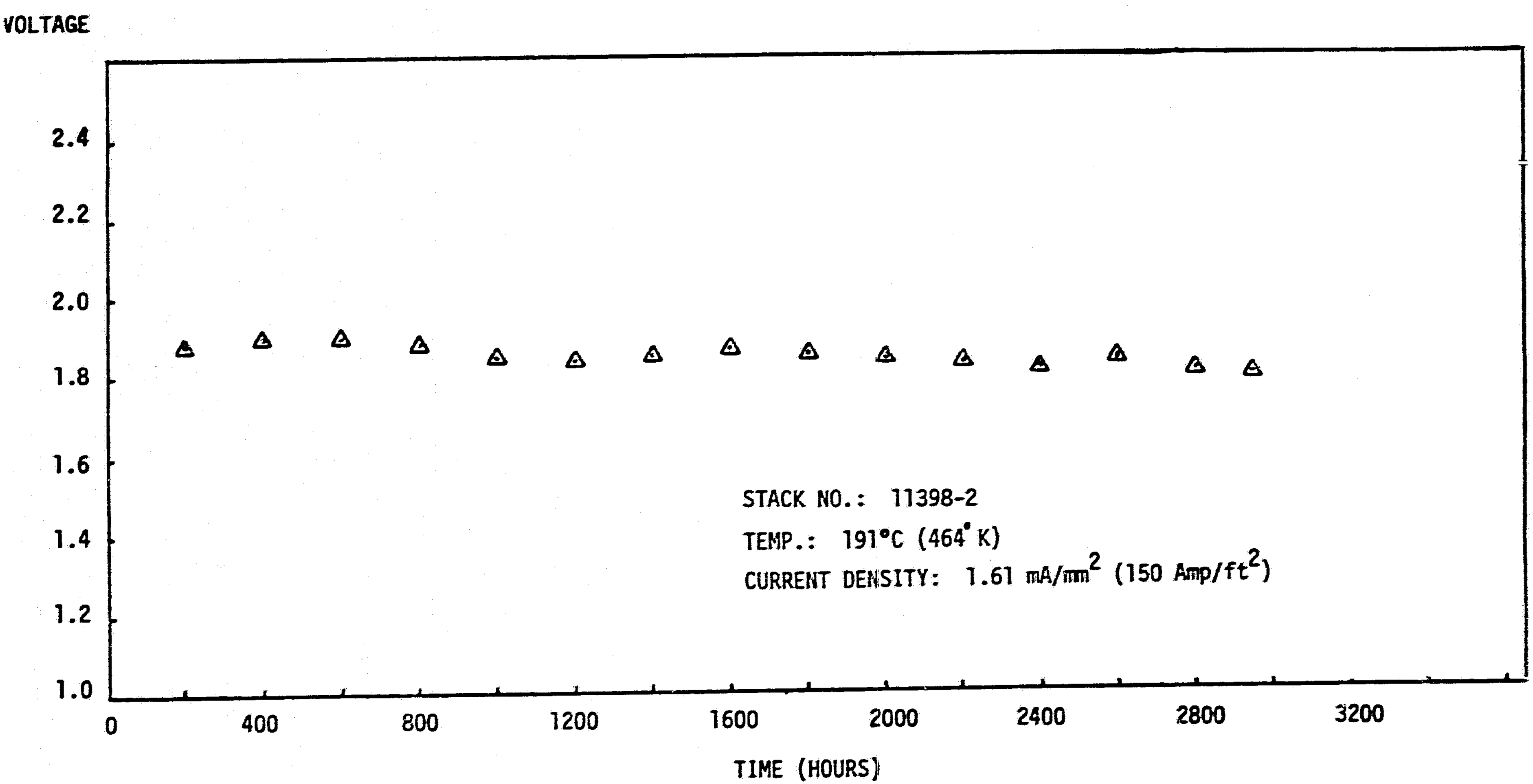
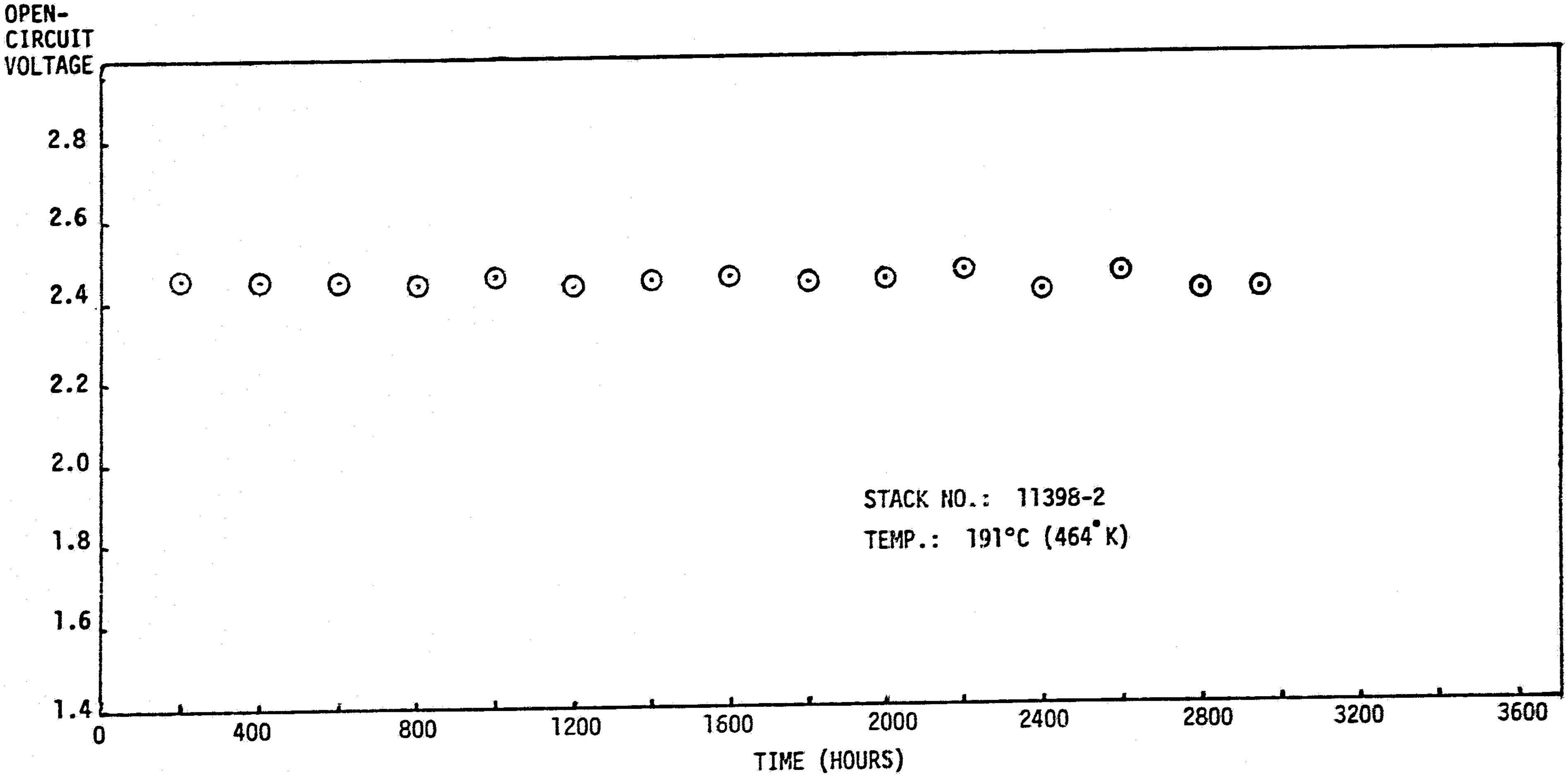


FIGURE 5 VOLTAGE STABILITY OF 3-CELL STACK WITH IMPROVED ELECTROLYTE MANAGEMENT SYSTEM



<u>FIGURE 6</u> <u>OPEN-CIRCUIT VOLTAGE STABILITY OF 3-CELL STACK WITH IMPROVED ELECTROLYTE MANAGEMENT SYSTEM</u>

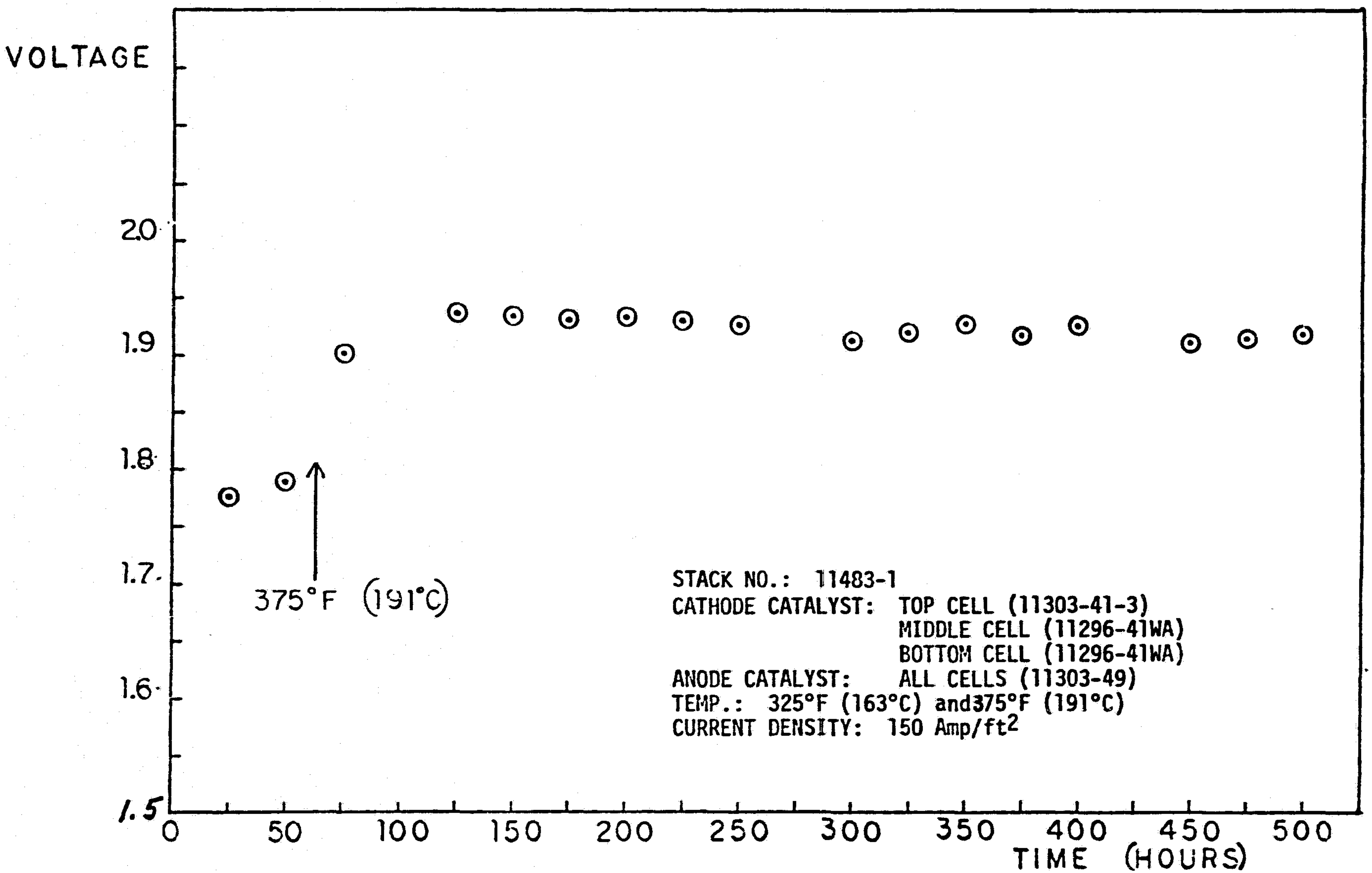


FIGURE 7

VOLTAGE STABILITY OF 3-CELL STACK UTILIZING: 1) IMPROVED ELECTROLYTE MANAGEMENT SYSTEM, 2) IMPROVED ELECTROCATALYSTS

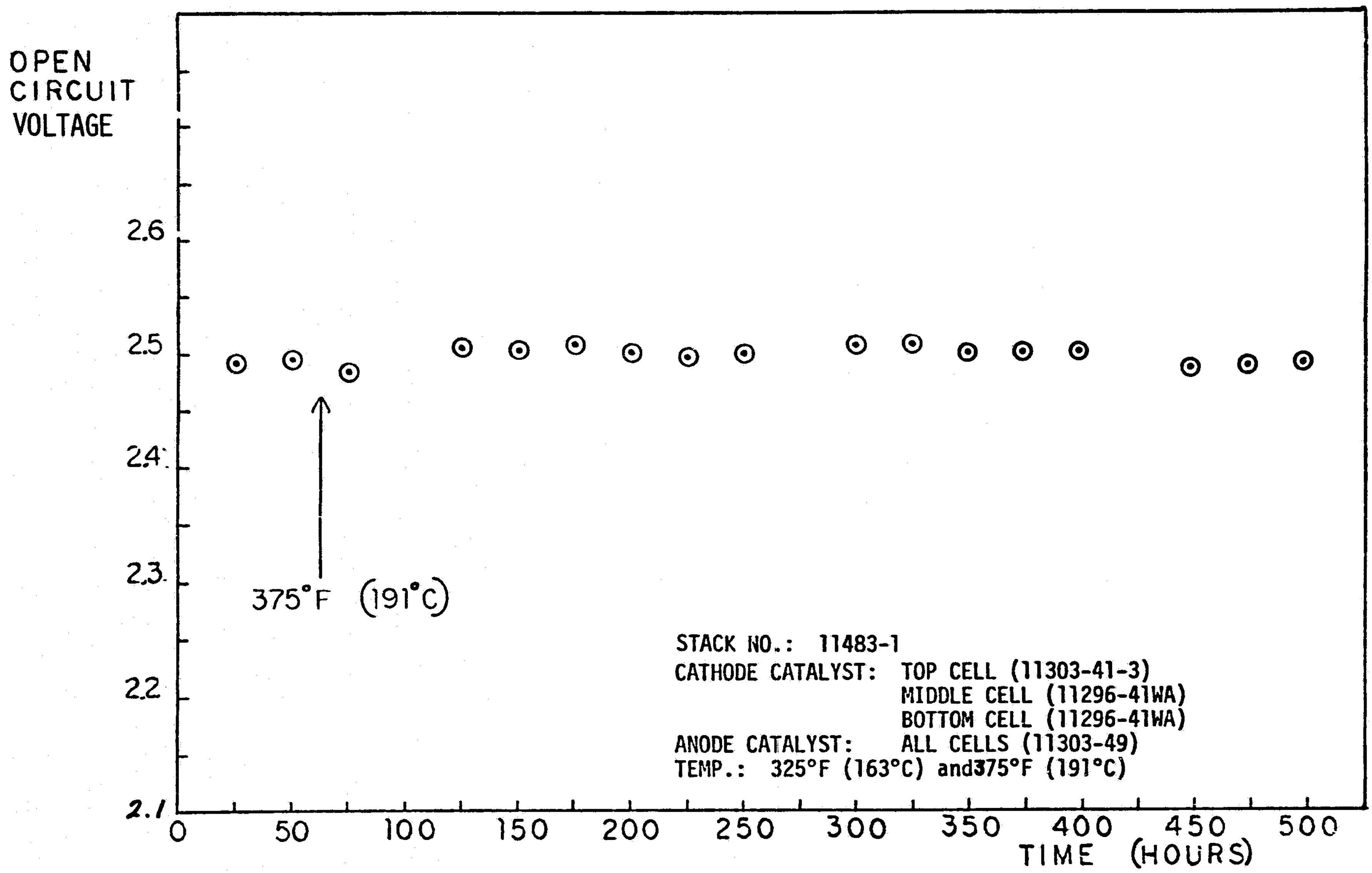


FIGURE 8

OPEN CIRCUIT VOLTAGE STABILITY OF 3-CELL STACK UTILIZING: 1) IMPROVED ELECTROLYTE MANAGEMENT SYSTEM, 2) IMPROVED ELECTROCATALYSTS

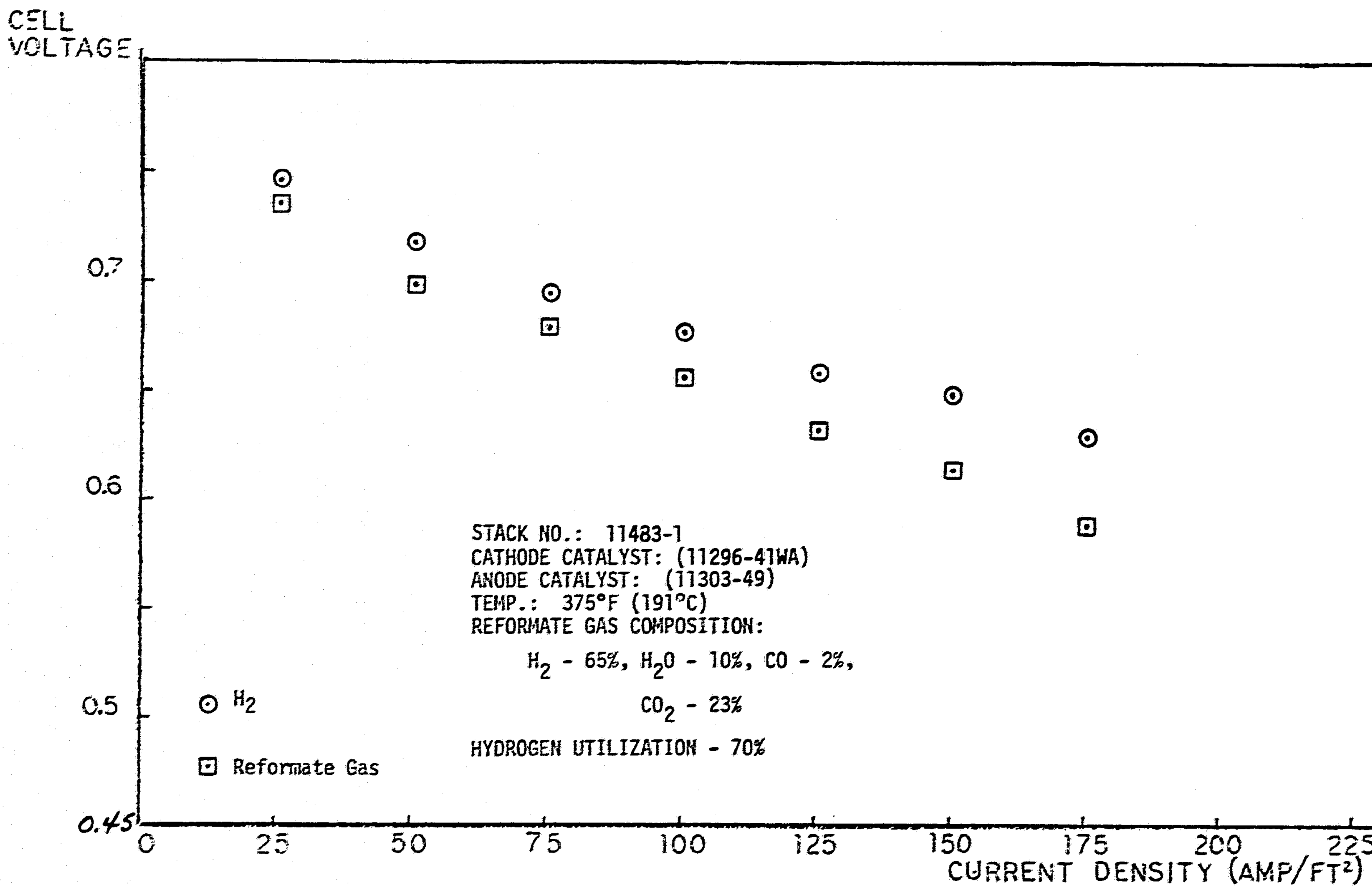


FIGURE 9 EFFECT OF REFORMATE GAS ON THE PERFORMANCE OF ONE CELL IN A THREE-CELL STACK UTILIZING AN IMPROVED ANODE ELECTROCATALYST

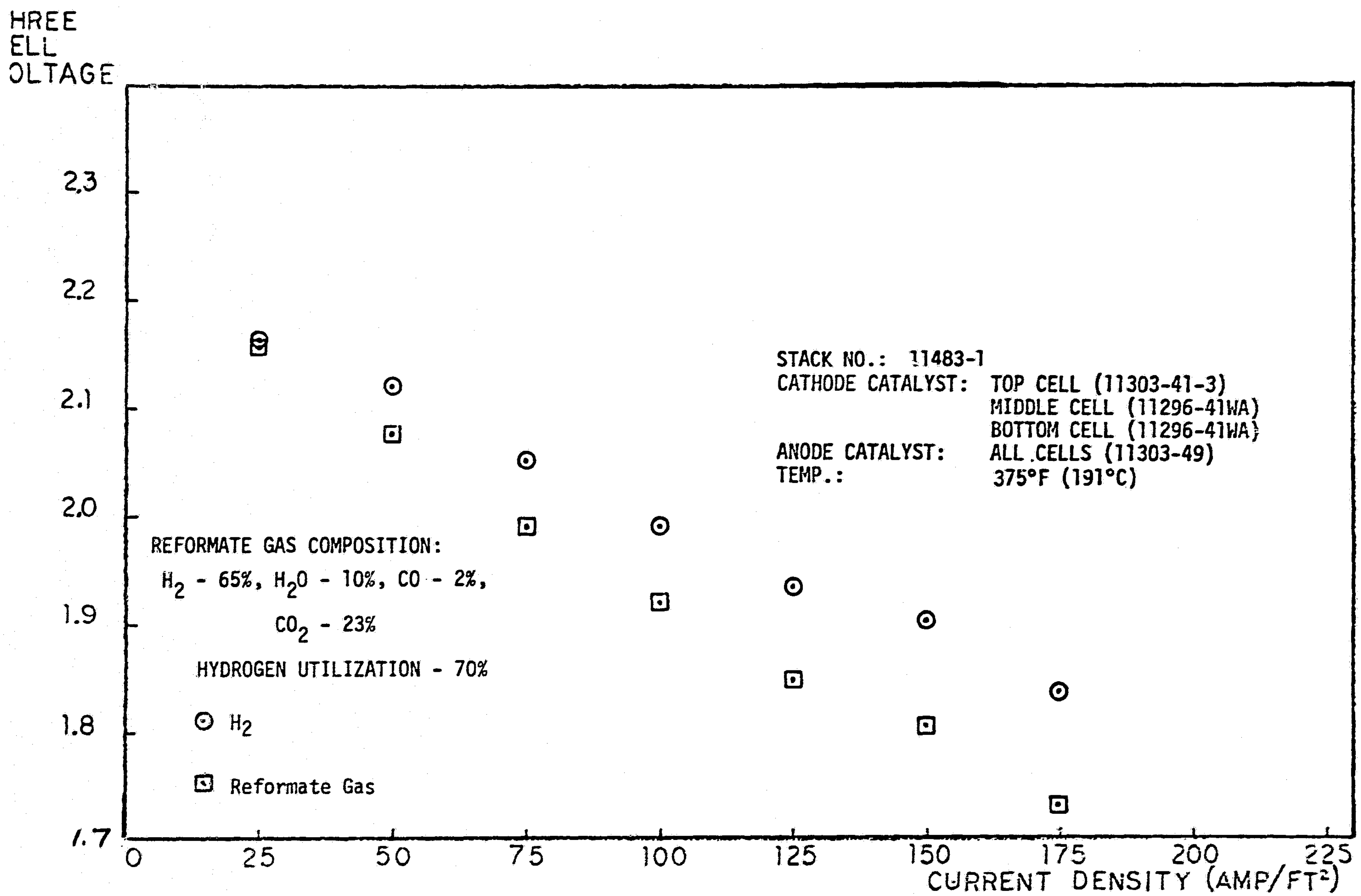


FIGURE 10 EFFECT OF REFORMATE GAS ON THE PERFORMANCE OF A 3-CELL STACK UTILIZING AN IMPROVED ANODE ELECTROCATALYST